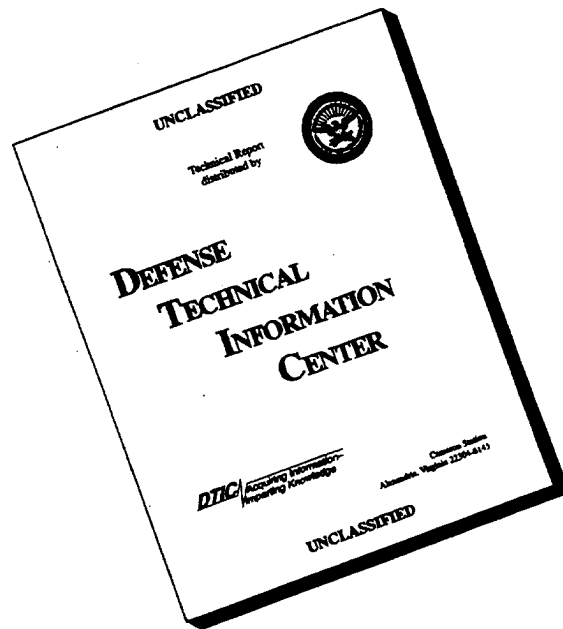


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**FINAL REPORT FOR THE GRANT  
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*Title:* Topics in shallow water noise generation and  
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*Principal Investigator:*  
Andrea Prosperetti  
Department of Mechanical Engineering  
The Johns Hopkins University  
Baltimore MD 21218

## Introduction

Our research in the past decade has uncovered the determinant role played by bubbles – and especially bubble clouds – in the generation and scattering of oceanic ambient noise.

The basic process at the root of these effects is of course the entrainment of bubbles below the water surface. The mechanisms by which this air entrainment is effected are also of considerable importance for the exchange of gases between the ocean and the atmosphere and in a variety of other natural and technological processes. Most of the work carried out during the period covered by the grant has been devoted to the study of air entrainment. Another achievement has been the formulation of an ambient noise model for shallow water.

Work has also been started on the scattering of underwater sound by a objects of simple shape. The purpose of this effort is to generate a series of essentially analytics solutions that can be used to benchmark propagation codes. Unfortunately the student in charge of this work turned out to be unsuitable and was dismissed. We plan to resume the work at a later time exploiting the conclusions reached so far.

The results attained in the course of the performance period of this grant are documented in the papers listed below. The first page of each paper is also reproduced. Additional information on the work carried out under this grant is provided in the annual summaries submitted to ONR and published in part in the series of annual volumes titled *Ocean Acoustics Program Summary*.

## Student support

Dr. Hasan N. Oğuz, a Research Associate Professor in the Department of Mechanical Engineering has given a most significant contribution to the work carried out under this grant.

In addition, the following students have been supported wholly or partially under the grant:

1. **Masao Watanabe.** Doctoral dissertation title: *Topics in Bubbly Liquid Flows and Cavitation*. Johns Hopkins, Doctoral degree awarded January 1995
2. **Xin Cheng.** Chinese, female; left program in May 1994
3. **Lei Zhang.** Chinese, male. Admitted September 1993; left program May 1995

## Papers

The following list does not include oral presentations at meetings of the Acoustical Society of America or at the American Physical Society Fluid Dynamics Division.

1. Arndt, R.E.A. and Prosperetti, A. eds. *Aeration Technology*, American Society of Mechanical Engineers, 1994.
2. Oğuz, H.N. and Prosperetti, A. Mechanics of air entrainment by a falling liquid. In *Aeration Technology*, Arndt, R.E.A. and Prosperetti, A. eds. American Society of Mechanical Engineers, 1994, pp. 13-20.
3. Prosperetti, A. Linear waves in bubbly liquids. In *Waves in Liquid/Gas and Liquid/Vapour Two-Phase Systems*, Morioka, S. and van Wijngaarden, L. eds. Kluwer, 1995, pp. 55-65.
4. Oğuz, H.N. Modeling of bubble clouds as sources of low frequency underwater noise. In *Sea Surface Sound*, Buckingham, M.J. and Potter, J.R. eds. World Scientific 1995, pp. 320-331.

5. Oğuz, H.N. and Prosperetti, A. Mechanics of air entrainment. In *Sea Surface Sound*, Buckingham, M.J. and Potter, J.R. eds. World Scientific 1995, pp. 342-350.
6. Oğuz, H.N., Prosperetti, A. and Kolaini, A.R. Air entrapment by a falling water mass, *J. Fluid Mech.* **294**, 181-207, 1995.
7. M.S. Longuet-Higgins and H.N. Oğuz, Critical microjets in collapsing cavities *J. Fluid Mech.* **290**, 183-201, 1995
8. H.N. Oğuz, A semi-analytical method for the noise emission of finite-size objects in shallow water. *J. Acoust. Soc. Am.*, submitted

*Andrew Prosser*

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# **AERATION TECHNOLOGY**

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## MECHANICS OF AIR ENTRAINMENT BY A FALLING LIQUID

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Johns Hopkins University  
Baltimore, Maryland

### Abstract

When a steady stream of liquid enters a larger body of liquid at rest, air entrainment occurs along the line where the surface of the falling liquid meets the free surface of the receiving liquid. Even though the flow may be nominally steady, the formation of the air bubbles by which air entrainment takes place is an inherently unsteady process. Disturbances on the surface of the liquid are singled out as the fundamental cause of entrainment in this study. A simple model that takes into account the effect of gravity, surface tension, and the length of the disturbance is proposed. A potential-flow boundary-integral method is employed to carry out a parametric study of the model in the Froude-Weber number parameter space. The results show that surface tension has negligible effect for Weber numbers greater than about 10. For sufficiently long disturbances, the volume of the detached bubble is found to be proportional to the Froude number. This dependence is explained by a simple scaling argument. For finite-length disturbances, an optimum Froude number for which the volume of the entrained bubble is maximum is found. Entrainment stops completely at large Froude numbers.

### 1 Introduction

Air entrainment at a free surface is a common occurrence with many important implications for industry as well as natural phenomena. A number of industrial processes require large gas-liquid interface areas that can be easily achieved by the entrainment of gas in the form of bubbles. Although not always desirable,

air entrainment also occurs in the filling of large tanks, pouring of molten glass, etc. Whitecaps resulting from breaking waves and white water under falls are nothing but mixtures of water and air bubbles entrained by the prevailing flow field. A complete characterization of the relevant factors is very difficult if not impossible in these highly complex flows. Therefore, there is a great incentive for a good understanding of the fundamental mechanisms that govern the process.

The first systematic study of air entrainment by jets falling into a liquid pool was done by Lin & Donnelly (1966) who were primarily interested in the effect of various factors on the onset of entrainment. For viscous liquids they found that a thin film of air is formed around the jet in the receiving liquid. At the point where the film becomes unstable, they observed small bubbles being shed into the liquid. Lezzi & Prosperetti (1991) recently gave a detailed account of the stability of this film. In contrast, less viscous liquids like water manifest a somewhat different mode of entrainment. In this case, bubbles are formed much closer to the free surface and the instability of the jet in the air is the main factor in this type of entrainment. Lin & Donnelly (1966) attributed this difference to the presence of disturbances on the jet surface. Burgess et al. (1972) further investigated this regime and concluded that the geometry of the nozzle from which the jet issues is an important factor. Van de Sande & Smith (1973, 1976) pointed out that very high velocity jets exhibit a marked increase in the entrainment rates mostly due to the change in the surface roughness of the jet. McKeogh & Ervine (1981) developed empirical correlations between air entrainment rates and jet surface roughness.



# LINEAR WAVES IN BUBBLY LIQUIDS

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**Abstract.** A summary of the current status of the modeling of the propagation of pressure waves in bubbly liquid is presented. An apparent failure of the theory near and above the resonance frequency of the bubbles is found by comparison with experimental data. In the second part of the paper applications to oceanic noise, laboratory bubble clouds, and resonance-parametric generation of low frequency underwater sound are described.

**Key words:** Bubbly liquids, Two-phase flow, Oceanic noise

## 1 Foldy's theory

The lowest-order theory of wave propagation in bubbly liquid was essentially worked out by Foldy in a well-known 1945 paper [3], and later applied by him and Carstensen to the analysis of data [4]. The following, although by no means rigorous, is a very simple derivation of Foldy's result.

In the context of potential flow theory, to leading order, bubbles behave as monopoles with strength given by  $\dot{v}$ , the time derivative of their volume. Consider then  $N$  bubbles immersed in an "incident" flow given by a potential  $\phi_\infty$ . The total flow due to the incident flow plus the effect of the bubbles has then the potential

$$\phi = \phi_\infty + \sum_{j=1}^N \frac{\dot{v}_j}{4\pi|x - x_j|}, \quad (1)$$

where  $x_j$  is the position of the  $j$ -th bubble. If  $N$  is large, the preceding relation may be approximated as

$$\phi \simeq \phi_\infty + \int \frac{\dot{v}}{4\pi|x - x'|} n(x') d^3x', \quad (2)$$

where  $n$  is the bubble number density. Upon taking the Laplacian of this expression, since  $\phi_\infty$  is regular in the region of interest, we have

$$\nabla^2 \phi = n\dot{v}, \quad (3)$$

which is essentially Foldy's result for an incompressible liquid. This can be written in a somewhat different form by noting that, for the linear problem,

$$u = \nabla \phi \quad P = -\rho \frac{\partial \phi}{\partial t}, \quad (4)$$

## MODELING OF BUBBLE CLOUDS AS SOURCES OF LOW FREQUENCY UNDERWATER NOISE

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The Johns Hopkins University,  
Baltimore, MD 21218

Wave breaking and subsequent formation of whitecaps are known to be the major contributor to the wind dependent ambient noise levels in the ocean in the low frequency range (100Hz-1kHz). A theoretical model that can account for the noise emissions from randomly distributed bubble clouds is developed in this study. The model assumes that individual whitecaps produce bubble plumes that grow as a result of air entrainment at the ocean surface. The injection of bubbles at the base of this plume excites the bubble cloud. The underwater ambient noise level is calculated by integrating contributions from bubble clouds of all sizes with minimal experimental input. The results are in good agreement with the field measurements.

### 1 Introduction

The correlation between the wind speeds and the underwater ambient noise levels has been known for some time (Knudsen et al 1948, Wenz 1962). Among many mechanisms proposed in the literature (Kewley et al 1990), the collective oscillations of bubbles (Carey & Bradley 1985, Prosperetti 1985) seem to be the most promising one. Recently, a great deal of attention has been paid to the study of noise emission from bubble clouds (Carey & Browning 1988, Prosperetti 1988, Lu et al 1990, Yoon et al 1991, Prosperetti et al, 1993, Nicholas et al 1994, Oguz 1994).

In this paper, our objective is to develop a model based on collective oscillations of bubble clouds to predict the ambient noise levels with minimal experimental input. We rely on the universality of the noise emission process to reduce the number of parameters in the system. The primary input to the model is the whitecap area coverage ratio. Monahan (1988) and Monahan & Lu (1990) gave a detailed account of the formation and classification of whitecaps. According to their observations there are three types labeled as  $\alpha$  or A,  $\beta$  or B and  $\gamma$ . In the current model, we will only consider type A whitecaps and neglect any contributions from type B and  $\gamma$  that are less energetic. Among the quantities that are assumed to be relatively insensitive to environmental conditions are bubble cloud void fraction, dipole moment strength, and size distribution of the entrained bubbles, growth-rate and size distribution of whitecaps. By using an empirical relation between the wind speed and the whitecap coverage ratio (Monahan 1988, Wu 1992) we can easily incorporate the wind dependence in our model.

## MECHANICS OF AIR ENTRAINMENT

A. Prosperetti and H.N. Oğuz  
Department of Mechanical Engineering  
Johns Hopkins University  
Baltimore MD 21218

**Abstract** Ambient noise production by bubbles presupposes air entrainment below the ocean surface. The purpose of this paper is to illustrate in a few idealized cases the basic mechanics of this process.

### 1 Introduction

In the last few years it has been realized that bubbles play a dominant role in the generation of oceanic ambient noise in a frequency range that extends from tens of Hz to possibly hundreds of kHz. These bubbles are entrained by relatively violent processes that are also responsible for imparting them the initial energy that causes them to pulsate and radiate sound. This process of air entrainment at a free surface is a complex phenomenon of great importance also in other natural settings and in industry. Despite its widespread occurrence, however, much is still to be learned about its fundamental mechanics. Aside from the pioneering paper by Lin and Donnelly (1966), virtually all the papers devoted to the subject report data of practical importance but shed little light on the underlying basic physics (Van de Sande and Smith 1973, 1976; Thomas et al. 1984; Sene 1988; McKeogh and Ervine 1981).

Our interest in the subject started with the study of the underwater noise of rain, which was found to be due to a small air bubble entrained by the impacting drops (Pumphrey and Crum 1990; Pumphrey and Elmore 1990; Oğuz and Prosperetti 1990, 1991; Prosperetti and Oğuz 1993), and continued with a short study of several qualitatively different entrainment mechanisms (Oğuz et al. 1992). Subsequently we have focussed our attention on the most promising of those mechanisms – the impact of water masses – which forms the object of the present paper.

All of the calculations described in this paper are based on an inviscid potential flow model. The numerical implementation is by means of a boundary integral method described in detail in our previous studies.

### 2 Splashes

We use the word “splash” to indicate the time-dependent flow due to the impact of a sizeable water mass on an initially plane water surface. In addition to dimensionless geometrical quantities such as shape, aspect ratio, impact angle, and others, a splash is characterized by

## Air entrapment by a falling water mass

By HASAN N. OĞUZ<sup>1</sup> ANDREA PROSPERETTI<sup>1</sup>  
AND ALI R. KOLAINI<sup>2</sup>

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(Received 13 September 1994 and in revised form 12 January 1995)

The impact of a nearly cylindrical water mass on a water surface is studied both experimentally and theoretically. The experiments consist of the rapid release of water from the bottom of a cylindrical container suspended above a large water tank and of the recording of the free-surface shape of the resulting crater with a high-speed camera. A bubble with a diameter of about twice that of the initial cylinder remains entrapped at the bottom of the crater when the aspect ratio and the energy of the falling water mass are sufficiently large. Many of the salient features of the phenomenon are explained on the basis of simple physical arguments. Boundary-integral potential-flow simulations of the process are also described. These numerical results are in fair to good agreement with the observations.

### 1. Introduction

The dull sound accompanying the falling of a mass of water onto a water surface is very commonly experienced. It was speculated by Minnaert (1933) and proven by Franz (1959) that this sound is caused by the oscillations of air bubbles, and it is the twin aspects of noise generation and air entrainment that motivate more than a passing interest in this process. On the acoustic side, it has been shown in recent years that air entrainment is the dominant contributor to oceanic ambient noise over a broad frequency range extending from a few tens of Hz to hundreds of kHz (Prosperetti 1988; Medwin & Beaky 1989; Medwin & Daniel 1990; Farmer & Ding 1992; Lamarre & Melville 1994; Loewen & Melville 1994; Hollett 1994; Ding & Farmer 1994; Kolaini & Crum 1994).

Depending on conditions (e.g. near the coast, or at very high sea states) an important fraction of the low-frequency component of this noise is directly due to waves breaking in the plunging mode and to the impact of splashes. In industry, air entrainment is actively pursued in certain water aeration systems and gas-liquid chemical reactors. Ship bow waves falling back onto the water surface also entrain bubbles that, in addition to causing noise, can be transported to the propeller region and act as nuclei for undesirable cavitation events. The process can also be encountered during the initial transient of an otherwise steady or quasi-steady flow such as a jet falling onto a liquid. Even when no air is entrained in the steady state, some bubbles may be generated when the jet first contacts the liquid surface.

Several recent papers have been devoted to the related process of air entrainment by impacting drops (Pumphrey & Crum 1988, 1990; Pumphrey, Crum & Bjørnø 1989; Pumphrey & Elmore 1990; Longuet-Higgins 1990; Oğuz & Prosperetti 1989, 1990, 1991; Prosperetti & Oğuz 1993; Chahine *et al.* 1991; Stroud & Marston 1993). In the

## Critical microjets in collapsing cavities

By MICHAEL S. LONGUET-HIGGINS<sup>1</sup> AND HASAN OGUZ<sup>2</sup>

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(Received 11 July 1994 and in revised form 28 November 1994)

Inward microjets are commonly observed in collapsing cavities, but here we show that jets with exceptionally high velocities and accelerations occur in certain critical flows dividing jet formation from bubble pinch-off. An example of the phenomenon occurs in the family of flows which evolve from a certain class of initial conditions: the initial flow field is that due to a moving point sink within the cavity.

A numerical study of the critical flow shows that in the neighbourhood of microjet formation the flow is self-similar. The local accelerations, velocities and distances scale as  $t^{\beta-2}$ ,  $t^{\beta-1}$  and  $t^{\beta}$  respectively, where  $\beta = 0.575$ . The velocity potential is approximately a spherical harmonic of degree  $\frac{1}{4}$ .

### 1. Introduction

Since the suggestion by Kornfeld & Suvorov (1944) that the damage to solid walls from cavitation bubbles may be due to the impact of high-speed, inward-pointing jets involved in bubble collapse, many experimental and numerical studies have been carried out which amply confirm this phenomenon. For references to the literature see for example Blake, Taib & Doherty (1986). The occurrence of high-speed jets has also been observed in bubbles bursting at a water surface (Blanchard & Woodcock 1980), in axisymmetric standing waves on water (Longuet-Higgins 1983) and in steep, two-dimensional waves meeting a vertical wall (Cooke & Peregrine 1981).

The above examples indicate that the spontaneous formation of high-speed jets at a time-dependent free surface is a general phenomenon of some interest. However, most theoretical studies have been numerical and there are few analytical models. The Dirichlet hyperboloid suggested by Longuet-Higgins (1983) can model only a part of the flow. The two-dimensional generalizations of the Dirichlet hyperbola suggested by Longuet-Higgins (1993, 1994) depend on F. John's semi-Lagrangian representation in a complex plane (John 1953), and cannot easily be extended to axisymmetric motions.

However, though we cannot expect to find many exact solutions satisfying the nonlinear free-surface conditions for all times  $t$ , nevertheless we can hope to make progress by studying solutions in which the initial conditions say at time  $t = 0$ , are given in terms of simple analytic functions, involving only a few parameters. We can then follow the development of the flow by numerical time stepping, using a boundary-integral technique, and see how this development changes as we vary the parameters of the initial flow.

Such was the approach adopted in the present paper. As a promising model we considered first the flow around a cavity in which there was a moving point source (or sink). The motion of the source introduces an asymmetry into the initial pressure distribution. At the same time, by allowing the strength  $S$  of the source to vary with

# Emission of sound by a semi-submerged object in shallow water

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Received

## ABSTRACT

A semi-analytical solution to the problem of noise emission by a finite size object in shallow water is described. The acoustic field near the object is formulated in spherical coordinates. An inner region is set up to satisfy bottom boundary conditions and the normal mode solution of the outer region is matched at some distance from the source. Several numerical examples related to noise emission from bubble clouds are given. Comparison with the method of images shows excellent agreement up to a certain distance from the source where the image solution is expected to be accurate. The technique is also extended to handle arbitrary sound speed profiles in water column by means of a novel method for calculating normal modes. The point source approximation that has been widely used in the literature is also discussed by comparing the normal mode coefficients. It is found that the validity of the point source solution depends very much on the local radiation characteristics of the source.

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# THE JOURNAL of the Acoustical Society of America

Vol. 95, No. 5, Pt. 2, May 1994

1:20

1pUW5. A theoretical model of bubble clouds as sources of noise in shallow water environment. Hasan N. Oguz. (Dept. of Mech. Eng., Johns Hopkins Univ., Baltimore, MD 21218)

Wave breaking that leads to bubble cloud formation is known to be a major contributor to the underwater noise levels in the low-frequency range (100 Hz–1 kHz). The emission theory that was developed by the author [Oguz, J. Acoust. Soc. Am. (to be published)] for deep ocean has been extended to handle shallow water environments. The model consists of a bubble cloud system excited by the injection of bubbles during a wave breaking event. The bottom effects are incorporated by the method of images. For simplicity, only the soft and hard bottom cases are considered in this development. The resonance characteristics of the bubble cloud are not affected by the presence of a bottom for depths much larger than the cloud size. However, the far-field acoustic pressure of an individual bubble cloud differs considerably from the deep water case due to the interference between the source and its images. As a result, the ambient noise level distribution in shallow water can be markedly different than in deep ocean. The results are compared with field measurements and a good agreement is found. [Work supported by the ONR.]

127th Meeting

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# BULLETIN

OF THE AMERICAN PHYSICAL SOCIETY

16:23

FA 7

A simplified description of the impact of a liquid mass on a liquid surface *H.N. Ögüz and A. Prosperetti, The Johns Hopkins University, A.R. Kolaini, NCPA, University of Mississippi.*

The impact of a liquid mass on a flat liquid surface is considered. This phenomenon causes air entrainment with consequences on underwater noise, gas exchange and cavitation strength.

among others. The impacting mass is taken to be a cylinder and the process is characterized by the Froude number and the aspect ratio. Among the quantities of interest are the radius of the entrained bubble, the size and depth of the crater, the penetration velocity, and the time of collapse. The entrance of the jet is modeled by a source in a uniform stream. The width of the crater is deducted from the Rankine body of this source. This and other predictions agree well with observations.

Work supported by the Underwater Acoustics Division of ONR.

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November 1994

Volume 39, No. 9

# THE JOURNAL of the Acoustical Society of America

Vol. 97, No. 5, Pt. 2, May 1995

2:20

X 2pAO2. Direct numerical simulation of the acoustic behavior of bubble clouds. M. Watanabe and A. Prosperetti (Dept. of Mech. Eng., Johns Hopkins Univ., Baltimore, MD 21218)

The description of a bubble assembly, or cloud, by means of an "effective medium" approximation has found widespread application in the underwater acoustics community. In this approach the bubbly liquid is regarded as a continuum endowed with properties different from those of the pure liquid. In this study the effective medium results are compared with those of a direct numerical simulation in which the effects of the mutual interaction of the bubbles are simulated. A spherical assembly of bubbles immersed in an incompressible liquid is studied. The potential problem is solved numerically with a singularity expansion method including both volume pulsations and translational oscillations of the bubbles. Numerical results for both single realizations and ensemble averages are presented and discussed. [Work supported by the Office of Naval Research.]

Program of the  
129th Meeting

Renaissance Washington, DC Hotel  
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# THE JOURNAL of the Acoustical Society of America

Vol. 97, No. 5, Pt. 2, May 1995

3:20

2pAO6. A model for underwater ambient noise at low wind speeds.  
Hasan N. Oguz (Dept. of Mech. Eng., Johns Hopkins Univ., Baltimore,  
MD 21218)

When the wind speed is low enough, wave breaking does not lead to bubble clouds of substantial size. The collective mode of oscillations that is dominant at high wind speeds may be neglected. In this case, wave breaking that is still the major source of noise is approximated by a finite area of the sea surface over which single bubbles are entrained and emit individual acoustic pulses. Each breaking wave has a certain emission characteristics depending on bubble size distribution, density, wave size, rate of entrainment, etc. An empirical correlation between the whitecap coverage ratio and the wind speed is employed to infer the size of the bubble entrainment area. The contribution of all waves are summed and the ambient noise levels are computed as a function of the wind speed. The results are in good agreement with field measurements. [Work supported by the Office of Naval Research.]

## Program of the 129th Meeting

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# THE JOURNAL of the Acoustical Society of America

Vol. 98, No. 5, Pt. 2, November 1995

11:15

5aPAb13. A study of the natural frequencies of spherical and distorted bubbles in open cavities. Andrea Prosperetti, Hasan N. Oguz, and Jun Zeng (Dept. of Mech. Eng., Johns Hopkins Univ., Baltimore, MD 21218)

The natural frequency of a bubble in an open, liquid-filled cavity is studied. A number of axisymmetric and three-dimensional configurations are considered such as a bubble in a cylindrical tube closed or open at one end and open at the other, a bubble between two parallel plates, a bubble in an open spherical cavity, and others. For bubbles that are smaller than the acoustic wavelength, the incompressible potential flow approximation is adequate. The natural frequency is computed by a boundary integral method. A slightly overexpanded bubble is allowed to relax and oscillate, and its frequency is measured by taking the Fourier transform of the volume pulsations. Alternately, a constant potential over the bubble surface is imposed and the natural frequency is calculated from the resulting volume flow rate of the bubble. These two techniques give nearly identical results for linear oscillations. For each geometry, spherical as well as distorted bubbles are investigated. [Work supported by the Office of Naval Research.]

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St. Louis, MO  
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# THE JOURNAL of the Acoustical Society of America

Vol. 98, No. 5, Pt. 2, November 1995

3:05

2pAO5. A semianalytical method for the noise emission of finite size objects in shallow water. Hasan N. Oguz (Dept. of Mech. Eng., Johns Hopkins Univ., Baltimore, MD 21218)

Point sources are commonly used in underwater ambient noise computations to model wave breaking noise. A semianalytical solution to sound emission by a finite size object in shallow water is developed. The coefficients of the normal modes obtained by this technique are compared with the coefficients given by the point source approximation for the case of a hemispherical bubble cloud. The comparison is only good when the size of the bubble cloud is much smaller than the acoustic wavelength. Substantial differences occur when the radiation pattern near the bubble

cloud deviates from a circular shape associated with the point dipole emission. Accurate normal modes coefficients given by the current method could be coupled with shallow water propagation models used in ambient noise calculations. [Work supported by the Office of Naval Research.]

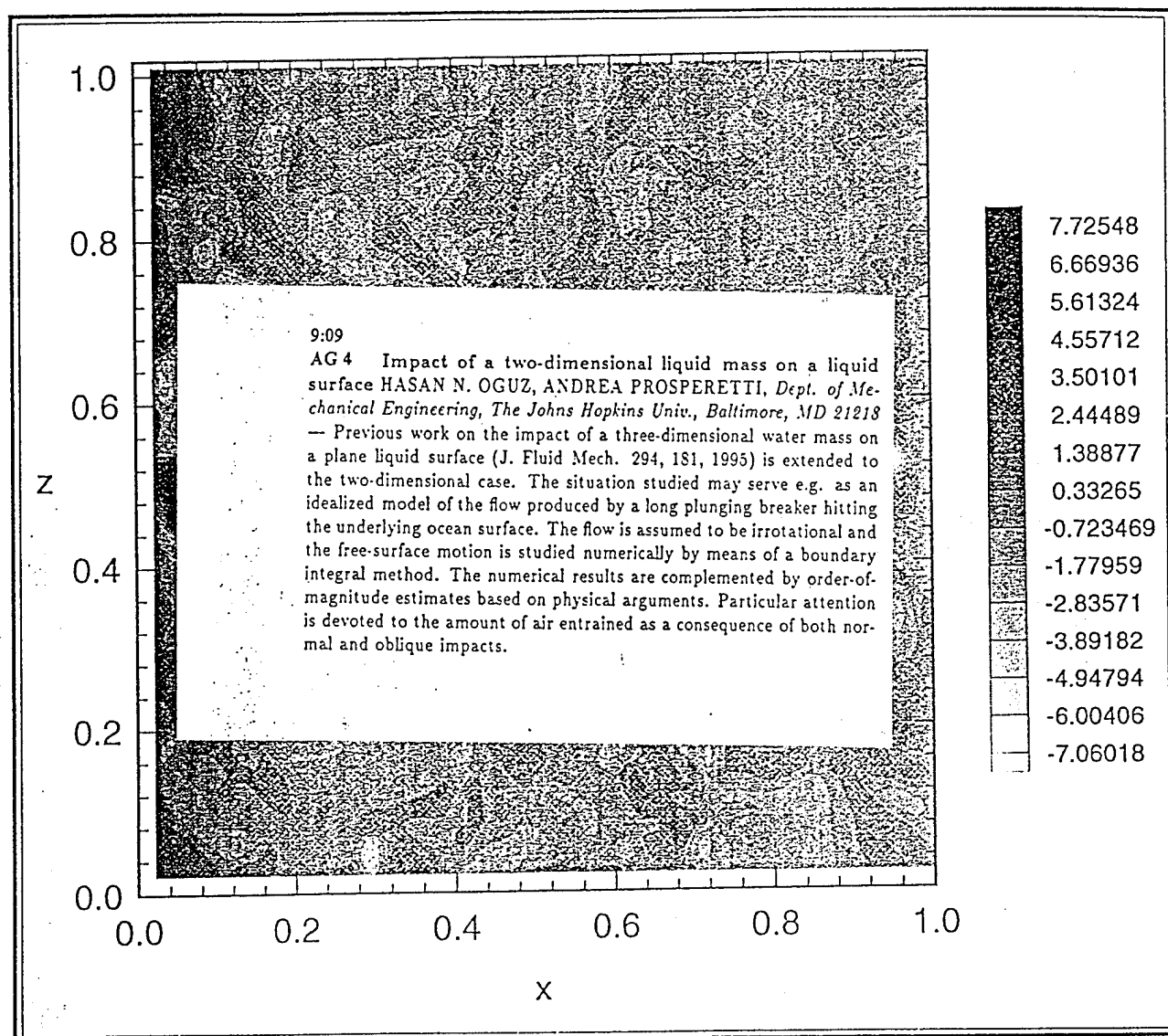
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# BULLETIN

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